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Wind power utilization for water pumping using small wind turbines in Saudi Arabia: A techno-economical review

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ABSTRACT

An attempt has been made, may be first time in Saudi Arabia, to utilize power of the wind for pumping the water for remotely located inhabitants not connected with national power grid. Small turbines of 1–10 kW have been chosen in conjunction with Goulds 45 J model water pumps to produce energy from wind and pump water using the produced energy at Arar, Rawdat Ben Habbas and Juaymah localities in Saudi Arabia. Wind speed measurements made at different heights using 40 m tall towers have been utilized in the present work. Higher wind speeds were noticed during summer time compared to winter time at all the locations. Both energy yield and cost of energy point of view, 2.5 kW wind turbine from Proven was found to be most suitable for wind power generation at all sites. It is shown that annual total water pumping capacity of 30,000 m^3 is possible from a depth of total dynamic head of 50 m when using 2.5 kW Proven wind turbine with hub heights 15–40 m at all three sites with cost of water pumping as low as 1.28 US¢/m^3.

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1. Introduction

Water accessibility and availability are the key issues arising in densely populated cities in developed and developing countries and Saudi Arabia is not an exception. Having vast land, the populations are scattered and located primarily in some major cities but largely in remote areas. Transportation of water to all of these localities is difficult to maintain continuously, especially remote locations in mountainous regions. Saudi Arabia is blessed with lot of wind resources in coastal areas and mountainous regions and hence encouraged to be utilized for water pumping. Power of the wind is a clean, inexhaustible, free, reliable, and renewable source of energy. To further add to its advantages, it is quick to install, require negligible maintenance, and it does have any political or geographical boundaries. Power of the wind has become the power technology of choice for a number of countries around the globe. According to Global Wind Energy Council Report [1], the world's wind power capacity grew by 22.5% in 2010, adding 35,802 MW to bring total installations to 194,390 MW. Almost one half of these additions were made in China, which experienced yet another year of approximately 65%

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growth. Newly added capacity of 2139 MW in India and some smaller additions in Japan, South Korea and Taiwan make Asia the biggest regional market for wind energy in 2010, with more than 19,022 MW of new capacity.

As a source of power, wind has been used for over 2000 years [2]. The wind power pumping applications are well known and include community and domestic water supply, cattle watering, irrigation, drainage and salt pans, Smulders [3]. Roughly the water head required for community, domestic and cattle watering varies from medium (10–30 m) and deep (> 30 m) and for remaining categories very low (3 m) and low (3–10 m). Back in 1986 and 1994, Smulders [4] and Smulders and de Jongh [5] presented the review of the state of the art in the field of wind pumping, its applications, economics and potential. Water pumping has been one of the main applications for wind power and there are more than a million wind pumps in regular use [6]. Small wind-electric systems have become quite popular [7] these days for pumping water from underground or lifting to tanks located high up due to greater flexibility over mechanical systems [8] and being able to spare electricity for other usages. Bowen et al. [9] reported practical experience related to 10 kW Bergey wind-electric hybrid power system operated in conjunction with a diesel back-up generator and found that the actual performance differed significantly from the manufacturer's data, partly due to furling in variable conditions [9].

Study related to possibilities of using wind energy for pumping water in various localities of Jordan was reported by Mohsen and Akash [10]. The results showed that power of the wind could be utilized at most of the eleven sites studied to pump groundwater in Jordan. Al-Suleimani and Rao [11] investigated the performance of a pump at different wind speeds and monthly water output against average wind speed and compared the outcome with the design values provided by the manufacturer. Authors concluded that wind energy can be used successfully to pump the groundwater in remote locations in Oman with adequate wind resources available. Bouzidi [12] reported utilization of wind energy resources for pumping the water in Adrar region of Algeria. They showed that wind power pumping system is viable both technically and economically in Adrar region compared to solar PV based water pumping system. Hammad [13] showed that mechanical photovoltaic wind pumping systems were economically cheaper than the diesel based water pumping system in Jordan.

Harries [14] presented a historical review of the design, field-testing and manufacturing experiences of BHEL in the development of wind pumps for water pumping in remote rural areas. The study outlined the challenges facing the dissemination of wind pumps in Africa and its benefits to rural and remote communities. Bragg and Schmidt [15] presented a procedure for optimum selection of pumps and windmills for a given water pumping situation. With information available on the wind intensity, pump and wind turbine characteristics, the best pump and turbine could be selected for the application. Previous works on the matching of pumps and windmills have been reported by Vadot [16] and Banas and Sullivan [17].

In Saudi Arabia, lot of work has been done on wind power resources assessment, hybrid power system design, wind measurements, and grid connected wind farm design as can be seen from references [18–26]. The present study proposes the utilization of wind power for water pumping in Saudi Arabia using wind speed data measured at different heights using 40 m tall towers.

Table 1
Site specific information of 40 m tall towers.

Location	Latitude (°N)	Longitude (°E)	Altitude (m)	Data period
Rawdat Ben Habbas	29.14	44.33	443	Sep. 2005 to Apr. 2010
Juaymah	26.80	49.90	20	Jul. 2006 to Apr. 2009
Arar	30.80	41.30	550	Jun. 1995 to Dec. 1998

2. Site and data description

The present work utilized wind speed data measured at 20, 30 and 40 m above ground level for a period of two to four years at Arar [27], Rawdat Ben Habbas [24] and Juaymah [23]. The site dependent details and data measurement periods are given in Table 1. At each height two sensors were installed and data was scanned every 3 s and was recorded every 10 min. The surface air temperature (°C), relative humidity (%), surface station pressure (in. of Hg), and global solar radiation (W/m^2) data was collected at 1.5 m above the ground surface. The operating ranges and accuracies of various sensors used for the measurements are given in Table 2. The data collection site at Rawdat Ben Habbas was an open area from all directions except a couple of warehouse shades and diesel storage tanks in the far vicinity of wind mast. The area around the wind mast in Juaymah was surrounded by government and private industries and power plants which are connected to the national electric grid. The Arar meteorological data measurement site was an open area from all directions. The land surface was comprised of small rocks.

3. Wind speed and plant capacity factor analysis

The wind measurements are usually made at 5–10 m above ground level then are extrapolated to higher heights using wind power law which provides a rough estimate of the wind speed and hence the wind energy. The annual mean wind speeds measured at different heights along with other relevant meteorological parameters (temperature-T, pressure-P, and relative humidity-RH) is summarized in Table 3. It is evident from this table that wind speed increases with height at all the stations. Annual variation of wind speed provides an insight into the availability and intensity of the wind during different years, which, in turn, facilitates the estimation of energy yield from the wind turbines or wind farms in the vicinity of the measurements. The annual trends of the wind speed also provide information about the increase or decrease in annual mean wind speed with upcoming years. In the present case, the annual mean wind speeds were calculated for complete years, which mean that the years with missing values even for five days were not considered in the analysis.

The annual mean wind speed variation over the data collection period from 2006 to 2009 at Rawdat Ben Habbas is shown in Fig. 1. The annual mean wind speed was observed to increase by 3% in 2007 compared with that in 2006 but decreased by 3%, 4%, and 1% in 2008 compared with that in 2007 at 20, 30 and 40 m measurement heights, respectively. With respect to height, the annual mean wind speed increased by 13.1% and 6.3% at 30 m and 40 m AGL compared with that at 20 m and 30 m respectively. At Juaymah, the wind speed data was available for only two complete years, namely 2007 and 2008, as shown in Fig. 2. As seen from this figure, the annual mean wind speed increased from 4.13 m/s to 4.81 m/s (16.6%) due to increase in measurement height from 10 m to 20 m. Similarly, an increase of 10.3% and 6.6% was noticed in annual mean wind speed values at 30 and 40 m

Table 2
Operating ranges and accuracies of various sensors used for data collection.

Item description	Technical information
Wind speed sensor, NRG#40 Cup anemometer	AC sine wave, Accuracy: 0.1 m/s, Range: 1–96 m/s Output: 0–125 Hz, Threshold: 0.78 m/s
Wind direction vane, NRG#200P Potentiometer	Accuracy: 1%, Range: 360° Mechanical, Output: 0-Exc. Voltage, Threshold: 1 m/s, Dead band: Max 8° and Typical 4°
Temperature sensor #110S Integrated circuit	Accuracy: ±1.1 °C, Range: −40 °C to 52.5 °C, Output: 0–2.5 V DC, Operating temperature range: −40 °C to 52.5 °C
Barometric pressure sensor BP20	Accuracy: ±15 mb, Range: 150–1150 mb, Output: Linear voltage
Relative humidity sensor RH-5 Polymer resistor	Accuracy: ±5%, Range: 0–95% Output: 0–5 V, Operating temperature range: −40 °C to 54 °C
Pyranometer Li-Cor #LI-200SA Global solar radiation	Accuracy: 1%, Range: 0–3000 W/m², Output: Voltage DC, Operating temperature range: −40 °C to 65 °C

Table 3
Annual mean values of meteorological parameters.

Location	Wind speed (m/s)			WSE	T	P	RH
	20 m	30 m	40 m		(°C)	(mb)	(%)
Rawdat Ben Habbas	4.76	5.36	5.74	0.286	24.24	941	21.7
Juaymah	4.87	5.37	5.69	0.274	26.58	1014	13.5
Arar	5.00	5.50	5.75	0.182	23.40	1009	34.0

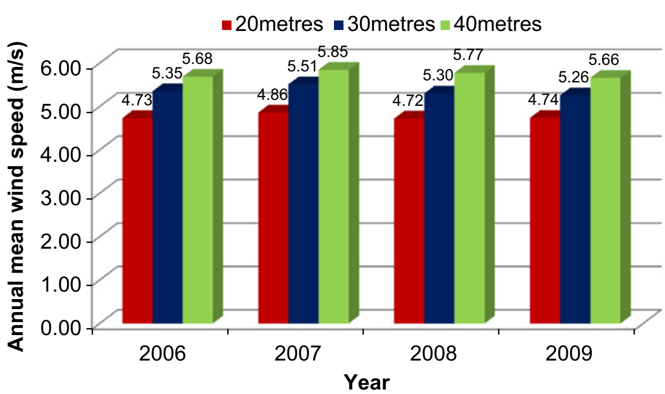


Fig. 1. Annual mean wind speed at different heights at Rawdat Ben Habbas.

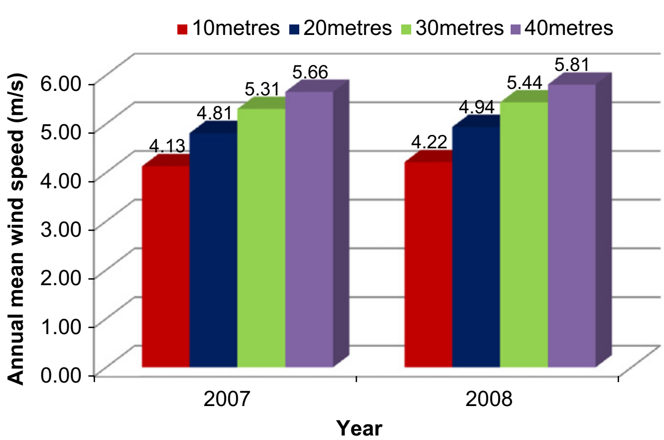


Fig. 2. Annual mean wind speed at different heights at Juaymah.

compared with those at 20 and 30 m AGL, respectively. The annual mean wind speed increased by 2.1% to 2.7% in year 2008 compared with that in 2007. At Arar, the annual wind speed values were available for 1996 and 1997, as shown in Fig. 3. The wind speed increased to 5.42 m/s at 30 m from 4.92 m/s at 20 m (an increase of 10.3%) and 5.65 m/s at 40 m from 5.42 m/s at 30 m (an increase of 4.2%) in the year 1996 while in 1997 these increases were 9.9% and 4.6%. From a year-to-year perspective,

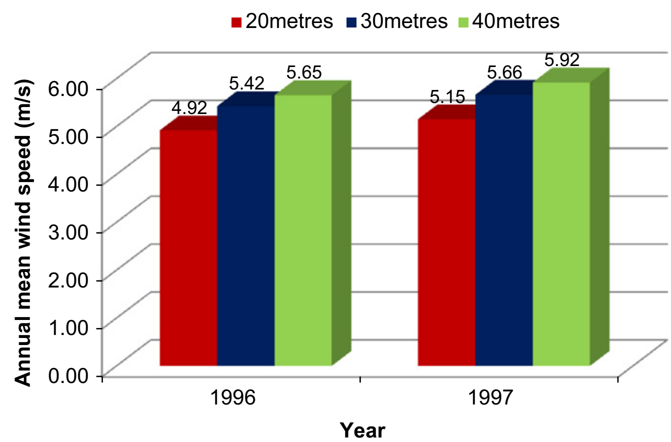


Fig. 3. Annual mean wind speed at different heights at Arar.

the annual mean wind speed increased by almost 4.5% at all the heights of measurements.

In the present analysis, the wind speed measured at 20, 30 and 40 m above ground level was used to determine the local wind shear exponents which in turn were used to estimate the wind speed at 15, 25 and 35 m. Following equation was used to estimate the wind speeds at different heights

$$WS2 = WS1 * \left(\frac{Z2}{Z1}\right)^{\alpha} \quad (1)$$

Where $WS1$ and $WS2$ are the wind speeds at heights $Z1$ and $Z2$, respectively and α is the local wind shear exponent. In the present case the values of α for Rawdat Ben Habbas, Juaymah, and Arar were determined using measured wind speeds at different heights and are 0.286, 0.274, and 0.182 respectively. The measured and estimated monthly mean wind speed at different heights at Arar, Rawdat Ben Habbas and Juaymah are given in Figs. 4–6, respectively. It is very evident the wind speed increases with height and hence results in higher energy yields. The seasonal trends of monthly mean wind speed show higher values in summer time and lower in winter, as depicted in Figs. 4–6.

4. Wind energy estimation

The technical information (Table 4) and wind power curves (Fig. 7) of the chosen wind turbines were obtained from Ref. [28] and the cost details from Refs. [29–31]. In order to address the water pumping applications in remote areas for individual to group of people, wind turbines of rated powers of 1–10 kW have been chosen for the generation of power and then its utilization for pumping the water in Arar, Rawdat Ben Habbas and Juaymah areas located in the eastern region of Saudi Arabia. The incremental cost of increasing hub height was taken as 116.67 US$/m

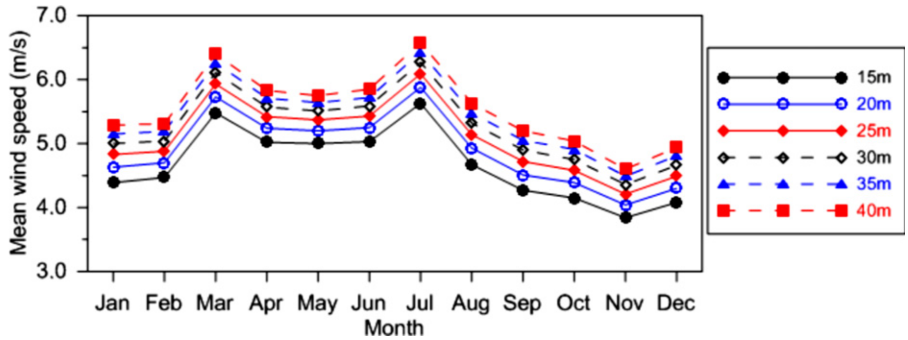


Fig. 4. Monthly mean wind speed variation with hub height at Arar.

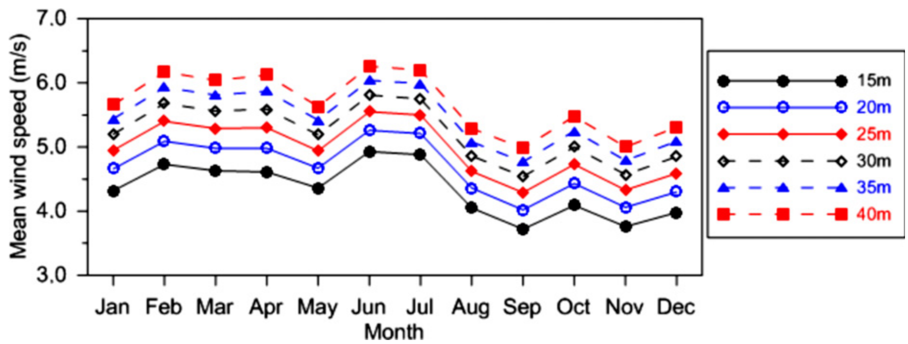


Fig. 5. Monthly mean wind speed variation with hub height at Rawdat Ben Habbas.

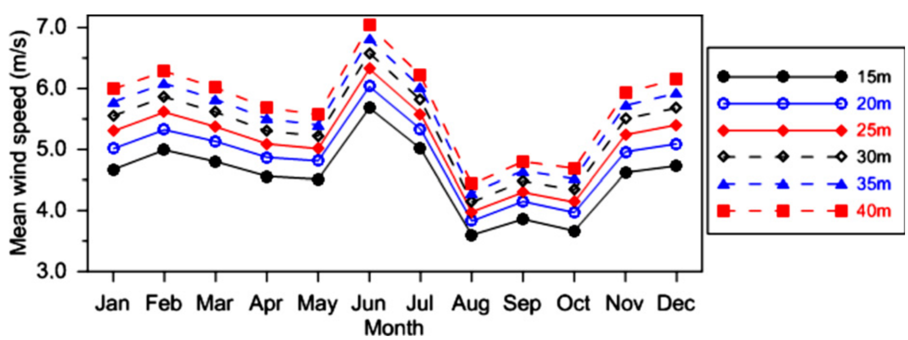


Fig. 6. Monthly mean wind speed variation with hub height at Juaymah.

Table 4
Technical financial specifications of the wind turbines used in the present work.

Turbine	Rated power (kW)	Rotor diameter (m)	Cut-in-speed (m/s)	Rated speed (m/s)	Swept area (m^2)	Turbine cost (US$)
Bergey XL.1	1.0	2.5	2.0	11	4.91	3450
Raum 1.3 kW	1.3	2.9	4.0	10	6.61	5150
Southwest Skystream 3.7	1.8	3.7	3.5	11	10.76	6962
Proven 2.5 kW	2.5	3.5	2.5	11	9.63	6150
Southwest Whisper 500	3.0	4.5	3.5	11	15.91	10,443
Bergey Excel-R 7.5 kW	7.5	6.7	4.0	11	35.27	32,000
Bergey Excel-S 10 kW	10.0	6.7	3.0	13	35.27	32,000

[29–31]. For a hub height of 15 m the cost of the tower 1750 US$ was added to the cost of the turbine provided in Table 4. Similarly, for additional heights the cost was added to the capital cost of the wind turbines.

The annual wind energy produced by each wind turbines at different hub heights using wind speed data from Arar is summarized in Table 5 and the related plant capacity factors are compared in Fig. 8. As expected, the wind energy yield and plant capacity factor (PCF) showed an increase with increasing hub heights as can be seen from Table 5 and Fig. 8, respectively. Moreover, the increase in PCF with hub height was almost linear for all the data sets as can be observed from Figs. 8–10. Wind turbine of 2.5 kW from Proven, showed the best performance both energy yield and PCF values point of view while Bergey 10 kW the least whereas wind regime in Arar is concerned.

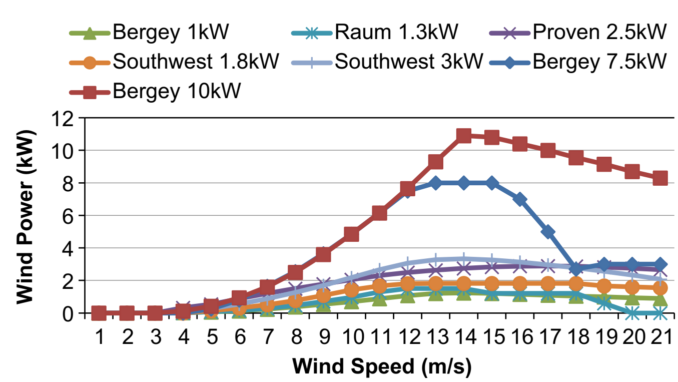


Fig. 7. Wind power curves of wind turbines used in the present work.

Table 5
Annual energy yield at different hub heights for Arar.

Turbine	Annual energy yield (kWh) Hub height (m)					
	15	20	25	30	35	40
Bergey XL. 1 kW	1369	1539	1692	1832	1962	2084
Raum 1.3 kW	1828	2043	2240	2423	2594	2756
Southwest Skystream 1.8 kW	2764	3094	3386	3649	3890	4113
Proven 2.5 kW	6187	6682	7092	7445	7757	8036
Southwest Whisper 3 kW	4710	5253	5727	6152	6541	6901
Bergey Excel-R 7.5 kW	8938	10,142	11,217	12,199	13,108	13,958
Bergey Excel-S 10 kW	9581	10,773	11,844	12,829	13,746	14,612

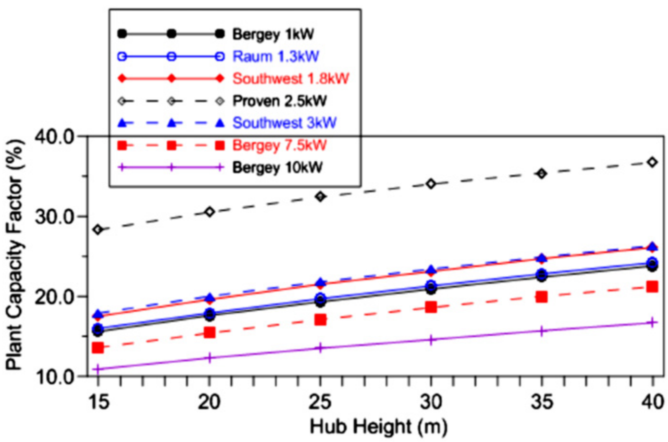


Fig. 8. Plant capacity factor variation with hub height at Arar for all turbines.

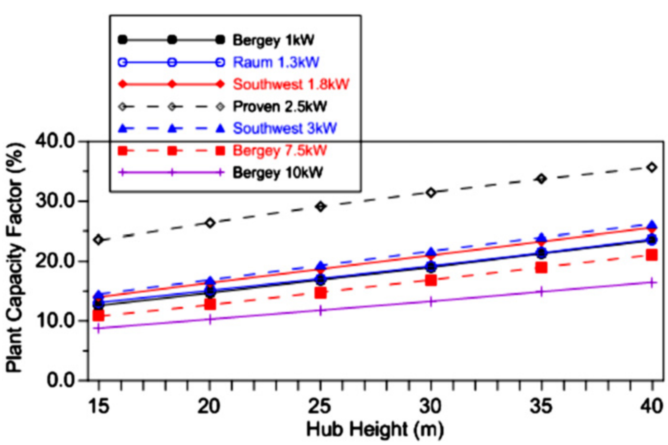


Fig. 9. Plant capacity factor variation with hub height at Rawdat Ben Habbas for all turbines.

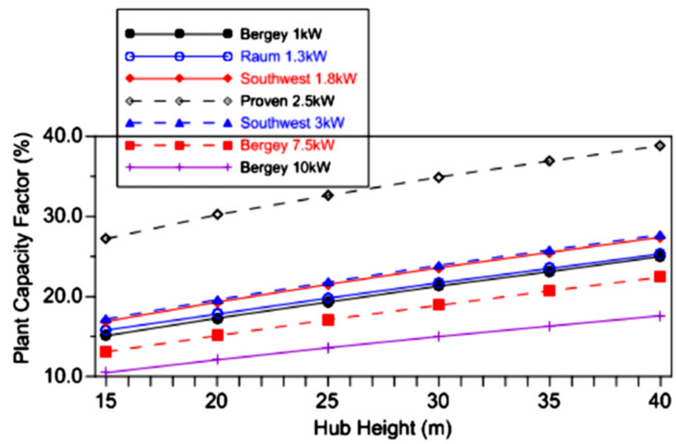


Fig. 10. Plant capacity factor variation with hub height at Juaymah for all turbines.

Table 6The PCF at Arar, Rawdat Ben Habbas, and Juaymah varied from 28.3–36.7%, 23.5–35.8%, and 27.2–38.8% corresponding to hub heights of 15–40 m and for 2.5 kW wind turbine form Proven Energy. On the other hand for Bergey 10 kW wind turbine, the PCF's varied from 10.9–16.7%, 8.8–16.5%, and 10.5–17.6% corresponding to hub heights of 15–40 m. It is evident from Tables 7–9 that maximum energy was obtained from all turbines in Arar while the minimum at Rawdat Ben Habbas. Similarly, the maximum values of PCF's were obtained at Arar and the minimum at Rawdat Ben Habbas (Figs. 8 and 9). The PCF values for all wind turbines at Jauymah are compared in Fig. 10. The wind turbines of 1.8 kW and 3 kW from southwest were found to be having the same performance whereas PCF is concerned at all the locations and were placed second in order of performance merit after 2.5 kW Proven wind turbine. Bergey 1 kW and Raum 1.3 kW showed close performance and were put at number three after Proven and Southwest wind turbines of 1.8 kW and 3 kW. Hence in order of performance the wind turbines can be put in order as follows:

Wind turbine of 2.5 kW from Proven Energy,
wind turbines of 1.8 kW and 3 kW from Southwest,
wind turbines of 1.3 kW and 1 kW from Raum and Bergey,
wind turbine of 7.5 kW from Bergey, and
wind turbine of 10 kW from Bergey.

5. Estimation of cost of wind energy (COE)

In order to estimate the cost of energy, the capital cost and the incremental cost (116.67 US$/m) of tower was taken into consideration. The capital cost also included the cost of voltage regulator, line-commutated inverter and installation. The operation and maintenance cost was not considered because no data is available for Saudi Arabia. The cost of energy (COE) was calculated by dividing the total cost by the total energy that could be produced over life time of the wind turbines (25 years in the present case). The COE values for Arar, Rawdat Ben Habbas, and Juaymah stations are summarized in Tables 8–10, respectively. Minimum COE was obtained for 2.5 kW Proven wind turbine for all the locations and all chosen hub heights. In general, maximum COE was obtained for Bergey 1 kW wind turbine at all hub heights and wind data sets from all locations. Furthermore, the COE values showed a decreasing trend with increasing hub height for all the wind turbines except 2.5 kW wind turbine from Proven Energy at Arar where COE decreased from 5.11 US¢/kWh to

Table 6
Annual energy yield at different hub heights for Rawdat Ben Habbas.

Turbine	Annual energy yield (kWh) Hub height (m)					
	15	20	25	30	35	40
Bergey XL. 1 kW	1106	1289	1476	1668	1863	2062
Raum 1.3 kW	1497	1717	1946	2187	2437	2695
Southwest Skystream 1.8 kW	2213	2586	2954	3319	3681	4038
Proven 2.5 kW	5140	5790	6371	6899	7381	7824
Southwest Whisper 3 kW	3804	4451	5080	5694	6295	6885
Bergey Excel-R 7.5 kW	7067	8369	9708	11,074	12,460	13,853
Bergey Excel-S 10 kW	7709	9023	10,340	11,677	13,040	14,428

Table 7
Annual energy yield at different hub heights for Juaymah.

Turbine	Annual energy yield (kWh) Hub height (m)					
	15	20	25	30	35	40
Bergey XL. 1 kW	1325	1514	1694	1864	2028	2187
Raum 1.3 kW	1796	2027	2254	2467	2676	2881
Southwest Skystream 1.8 kW	2661	3042	3391	3717	4026	4324
Proven 2.5 kW	5962	6624	7142	7635	8085	8497
Southwest Whisper 3 kW	4509	5156	5735	6276	6784	7268
Bergey Excel-R 7.5 kW	8622	9937	11,225	12,427	13,584	14,704
Bergey Excel-S 10 kW	9212	10,585	11,883	13,101	14,272	15,411

Table 8
COE based on capital and hub height incremental cost for Arar.

Turbine	COE (US¢/kWh) with hub height Hub height (m)					
	15	20	25	30	35	40
Bergey XL. 1 kW	15.19	15.03	15.05	15.17	15.36	15.58
Raum 1.3 kW	15.10	14.65	14.41	14.28	14.24	14.25
Southwest Skystream 1.8 kW	12.61	12.02	11.67	11.47	11.36	11.31
Proven 2.5 kW	5.11	5.08	5.11	5.18	5.28	5.38
Southwest Whisper 3 kW	10.35	9.73	9.33	9.07	8.88	8.76
Bergey Excel-R 7.5 kW	15.10	13.54	12.45	11.64	11.01	10.51
Bergey Excel-S 10 kW	14.09	12.75	11.79	11.07	10.50	10.04

Table 9
COE based on capital and hub height incremental cost for Rawdat Ben Habbas.

Turbine	COE (US¢/kWh) with hub height Hub height (m)					
	15	20	25	30	35	40
Bergey XL. 1 kW	18.81	17.95	17.25	16.67	16.17	15.75
Raum 1.3 kW	18.44	17.43	16.58	15.82	15.15	14.57
Southwest Skystream 1.8 kW	15.75	14.38	13.38	12.61	12.00	11.52
Proven 2.5 kW	6.15	5.86	5.69	5.60	5.55	5.53
Southwest Whisper 3 kW	12.82	11.48	10.52	9.79	9.23	8.78
Bergey Excel-R 7.5 kW	19.10	16.41	14.39	12.82	11.58	10.59
Bergey Excel-S 10 kW	17.51	15.22	13.51	12.16	11.07	10.17

5.08 US¢/kWh as the hub height increased from 15 m to 20 m and then increased to 5.11, 5.18, 5.28, and 5.38 US¢/kWh corresponding to hub heights of 25, 30, 35, and 40 m.

Table 10
COE based on capital and hub height incremental cost for Juaymah.

Turbine	COE (US¢/kWh) with hub height Hub height (m)					
	15	20	25	30	35	40
Bergey XL. 1 kW	15.70	15.28	15.03	14.91	14.86	14.85
Raum 1.3 kW	15.37	14.77	14.32	14.03	13.80	13.63
Southwest Skystream 1.8 kW	13.10	12.22	11.65	11.26	10.97	10.76
Proven 2.5 kW	5.30	5.12	5.08	5.06	5.06	5.09
Southwest Whisper 3 kW	10.82	9.91	9.32	8.89	8.56	8.32
Bergey Excel-R 7.5 kW	15.66	13.82	12.44	11.43	10.63	9.97
Bergey Excel-S 10 kW	14.65	12.97	11.75	10.84	10.11	9.52

6. Water pumping potential

Monthly variations of total electrical energy yield from Proven (2.5 kW) wind turbine at three different sites, namely, Arar, Rawdat Ben Habbas (RBH) and Juaymah, are given in Table 11. In this section, we consider only the 2.5 kW wind turbine from Proven Energy due to its lowest COE for all the three sites. Calculations of monthly total energy yield were carried out at six different hub heights, i.e. 15, 20, 25, 30, 35, and 40 m. The energy generated by the wind turbine is considered to operate Goulds 45 J models of submersible pumps for pumping underground water. The efficiency of Goulds 45 J model pumps is 62%. The water pumping capacity rate of these pumps are related to the size (power) of pumps and can be expressed as

$$\text{Flow capacity rate } (m^4/\text{hr}) = 227.87 \times \text{Power (kW)} \quad (2)$$

Eq. (2) indicates that these pumps yield 227.87 m^4 of pumping capacity per kWh energy. If the total dynamic head (TDH) of 50 m is considered, for example, then the volumetric yield of these

Table 11
Monthly energy yield of Proven (2.5 kW) wind turbine at different hub heights and corresponding monthly total water pumping capacities using Goulds 45 J series of submersible pumps for a total dynamic head (TDH) of 50 m. (a) Arar, (b) RBH, (c) Juaymah.

Month	Hub height (m)											
	15 m		20 m		25 m		30 m		35 m		40 m	
	kWh	Capacity (m^3)	kWh	Capacity (m^3)	kWh	Capacity (m^3)	kWh	Capacity (m^3)	kWh	Capacity (m^3)	kWh	Capacity (m^3)
(a)												
Jan	476	2169	520	2370	556	2534	588	2680	616	2807	642	2926
Feb	441	2010	477	2174	507	2311	533	2429	556	2534	577	2630
Mar	659	3003	704	3208	740	3372	770	3509	797	3632	821	3742
Apr	560	2552	598	2725	629	2867	656	2990	680	3099	701	3195
May	580	2643	617	2812	647	2949	671	3058	693	3158	713	3249
Jun	573	2611	612	2789	645	2940	672	3063	696	3172	717	3268
Jul	703	3204	750	3418	789	3596	821	3742	850	3874	875	3988
Aug	529	2411	576	2625	615	2803	648	2953	677	3085	703	3204
Sep	438	1996	482	2197	518	2361	550	2507	577	2630	603	2748
Oct	435	1982	477	2174	512	2333	543	2475	571	2602	596	2716
Nov	370	1686	405	1846	434	1978	460	2096	483	2201	504	2297
Dec	418	1905	459	2092	493	2247	524	2388	551	2511	576	2625
Annual	**6187**	28,197	**6682**	30,453	**7092**	32,321	**7445**	33,930	**7757**	35,352	**8036**	36,623
(b)												
Jan	457	2083	515	2347	567	2584	614	2798	656	2990	695	3167
Feb	472	2151	527	2402	576	2625	620	2826	659	3003	695	3167
Mar	496	2260	554	2525	605	2757	651	2967	693	3158	731	3331
Apr	473	2156	530	2415	580	2643	627	2857	669	3049	708	3227
May	437	1992	488	2224	534	2434	575	2621	613	2794	648	2953
Jun	504	2297	558	2543	605	2757	647	2949	685	3122	720	3281
Jul	505	2301	560	2552	609	2775	652	2971	690	3145	726	3309
Aug	369	1682	419	1910	464	2115	504	2297	542	2470	576	2625
Sep	313	1426	361	1645	405	1846	445	2028	483	2201	518	2361
Oct	393	1791	449	2046	500	2279	547	2493	590	2689	629	2867
Nov	336	1531	385	1755	429	1955	471	2147	509	2320	545	2484
Dec	392	1787	449	2046	500	2279	547	2493	590	2689	630	2871
Annual	**5140**	23,425	**5790**	26,387	**6371**	29,035	**6899**	31,442	**7381**	33,638	**7824**	35,657
(c)												
Jan	557	2538	621	2830	678	3090	729	3322	774	3527	815	3714
Feb	551	2511	605	2757	653	2976	694	3163	732	3336	765	3486
Mar	564	2570	623	2839	669	3049	713	3249	753	3432	789	3596
Apr	494	2251	547	2493	585	2666	624	2844	659	3003	691	3149
May	493	2247	544	2479	580	2643	616	2807	650	2962	681	3104
Jun	666	3035	723	3295	772	3518	816	3719	854	3892	889	4052
Jul	571	2602	627	2857	670	3053	710	3236	747	3404	780	3555
Aug	338	1540	375	1709	399	1818	426	1941	451	2055	475	2165
Sep	370	1686	415	1891	441	2010	473	2156	502	2288	529	2411
Oct	347	1581	397	1809	428	1951	464	2115	497	2265	529	2411
Nov	507	2311	571	2602	624	2844	673	3067	716	3263	756	3445
Dec	559	2548	629	2867	693	3158	748	3409	798	3637	843	3842
Annual	**5962**	27,171	**6624**	30,188	**7142**	32,549	**7635**	34,796	**8085**	36,847	**8497**	38,724

pumps is obtained to be 227.87/50=4.56 m^3 per kWh energy. The amounts of monthly total water pumping capacity corresponding to the total monthly energy yield figures are calculated and are given in Table 11 at different hub heights and three different sites. The annual total water pumping capacity for the same hub heights and sites are also included in the table.

Fig. 11 shows monthly total water pumping capacity from the wind energy water pumping system that consists of 2.5 kW wind turbine from Proven Energy Company and Goulds 45 J model pumps at Arar, RBH and Juaymah sites and for hubs heights varying from 15 m to 40 m. Water pumping capacity is generally high during the Spring and Summer months when demand for water is higher for irrigation purposes. This is due to the higher wind speeds available during these seasons. The range of water pumping capacity varies from 1500 to 4000 m^3 per month. This corresponds to daily average of 50–135 m^3 of water pumping capacity. The water pumping capacity is the lowest during the fall season. A consistent increase in the water pumping capacity is observed as the hub height is increased. This is pronounced for the site of RBH as can be seed in Fig. 12(b). Fluctuation in the monthly water pumping capacity throughout the year is less for the site of RBH when compared with that in the sites of Arar and Juaimah.

Cost analysis of water pumping at Arar, RBH, and Juaymah is given in Table 12. Cost of wind 2.5 kW wind turbine from Proven Energy Company including the cost of tower is given for different hub heights varying from 15 m to 40 m. In this analysis 3 hp Goulds 45 J series submersible pump is considered for underground water pumping purposes. The pump life is assumed to be 10 years while the life of wind turbine is taken to be 25 years. Thus, the total cost of wind turbine and pump for the period of 25 years is calculated. On the other hand the annual total volumetric water pumping capacity is evaluated at different hub heights and sites. Finally, the cost of pumping water from a depth of TDH 50 m is determined under these conditions.

Fig. 12 shows the annual total water pumping capacity of wind water pumping station consisting of 2.5 kW Proven wind turbine and 3 hp Goulds 45 J series submersible pump as

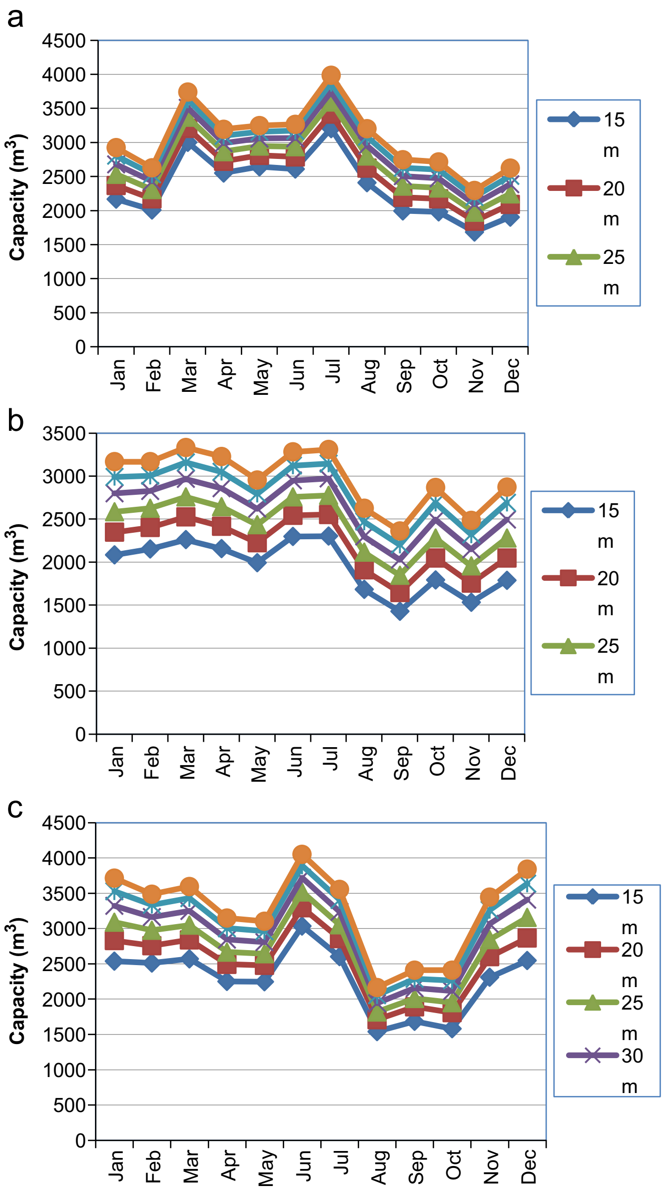


Fig. 11. Monthly total water pumping capacity of Proven (2.5 kW) wind turbine with different hub heights operating Goulds 45 J series of submersible pumps for a total dynamic head (TDH) of 50 m. (a) Arar, (b) RBH, (c) Juaymah.

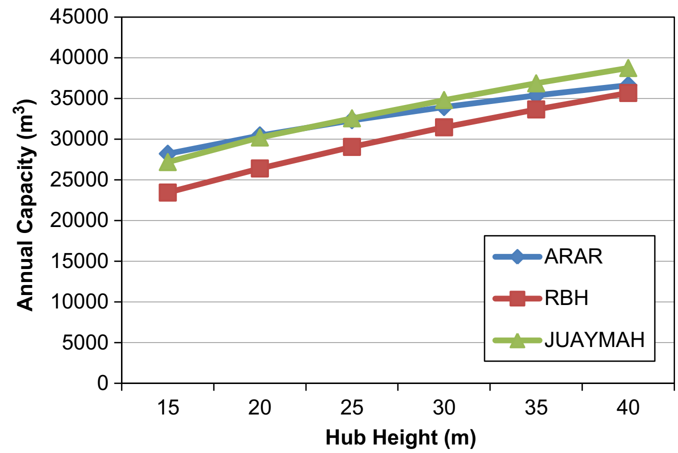


Fig. 12. Annual total water pumpign capacity of wind water pumping station consisting of 2.5 kW Proven wind turbine and 3 hp Goulds 45 J series submersible pump as function of hub height for a TDH of 50 m.

function of hub height for a TDH of 50 m. Water pumping capacity increases with the hub height in all the sites. However, the increase in the water pumping capacity with hub height for Arar site is less than the other two sites. Annual total water pumping capacity varies between 23,500–38,500 m^3. On the other hand, cost of water pumping at Arar, RBH and Juaymah sites as function of the hub heights is shown Fig. 13. In general, the cost of water pumping decreases with hub height except for Arar site. In Arar site the cost of water pumping initially decreases as the hub height is increases from 15 m to 25 m, reaching a minimum at 25 m hub height and then starts increasing as the hub height is increases further. However, the variation in the cost of water pumping in Arar site is not much and increasing the hub height for this site is not justified. The cost of water pumping in Arar site varied between 1.30 US¢/m^3 and 1.35 US¢/m^3. On the other hand, cost variation for the site RBH is considerable. Cost saving of nearly 20% is possible for RBH site as the hub height is increased from 15 m to 40 m. Cost saving in water pumping at Juaymah site appears to be on the order of 10% when using 40 m hub height. Cost of wind water pumping at Juaymah site for the hub height of 40 m and TDH of 50 m is found to be as low as 1.28 US¢/m^3.

7. Conclusions

In the recent years, it is the first attempt to utilize power of the wind for water pumping in Saudi Arabia. To accomplish the goals, wind speed data measured at different heights at Arar, Rawdat Ben Habbas and Juaymah using 40 m tall towers was used to estimate the local wind shear exponents and then extrapolation or interpolation of wind speeds to required hub heights using local wind shear exponents. Following major points have been noticed in the present work:

- The wind speed showed increasing trends with hub heights and higher values were observed during summer compared to winter time.
- The wind energy yield and plant capacity factor (PCF) showed an increase with increasing hub heights. The increase in PCF with hub height was almost linear for all the data sets used in the present work.
- Wind turbine of 2.5 kW from Proven, showed the best performance both energy yield and PCF values point of view while Bergey 10 kW the least whereas wind regime in Arar is concerned.
- The PCF at Arar, Rawdat Ben Habbas, and Juaymah varied from 28.3–36.7%, 23.5–35.8%, and 27.2–38.8% corresponding to hub heights of 15–40 m and for 2.5 kW wind turbine form Proven Energy. On the other hand for Bergey 10 kW wind turbine, the PCF's varied from 10.9–16.7%, 8.8–16.5%, and 10.5–17.6% corresponding to hub heights of 15–40 m.
- Maximum energy was obtained from all turbines in Arar while the minimum at Rawdat Ben Habbas. Similarly, the maximum values of PCF's were obtained at Arar and the minimum at Rawdat Ben Habbas.
- The wind turbines of 1.8 kW and 3 kW from southwest were found to be having the same performance whereas PCF is concerned at all the locations and were placed second in order of performance merit after 2.5 kW Proven wind turbine. Bergey 1 kW and Raum 1.3 kW showed close performance and were put at number three after Proven and Southwest wind turbines of 1.8 kW and 3 kW.

Table 12
Cost analysis of wind water pumping at Arar, RBH, and Juaymah sites with various wind turbine hub heights and TDH of 50 m.

Hub height (m)	Cost of wind turbine (US$)	Total cost of turbine and pump (US$)	Total annual energy yield (kWh)			Total annual volumetric water pumping capacity (m^3)			Cost of water for TDH = 50 m (US¢/m^3)		
			ARAR	RBH	JUAYMAH	ARAR	RBH	JUAYMAH	ARAR	RBH	JUAYMAH
15	7900	9475	6187	5140	5962	28,197	23,425	27,171	1.344	1.62	1.39
20	8483	10,058	6682	5790	6624	30,453	26,387	30,188	1.321	1.52	1.33
25	9067	10,642	7092	6371	7142	32,321	29,035	32,549	1.317	1.47	1.31
30	9650	11,225	7445	6899	7635	33,930	31,442	34,796	1.323	1.43	1.29
35	10233	11,808	7757	7381	8085	35,352	33,638	36,847	1.336	1.40	1.28
40	10817	12,392	8036	7824	8497	36,623	35,657	38,724	1.353	1.39	1.28

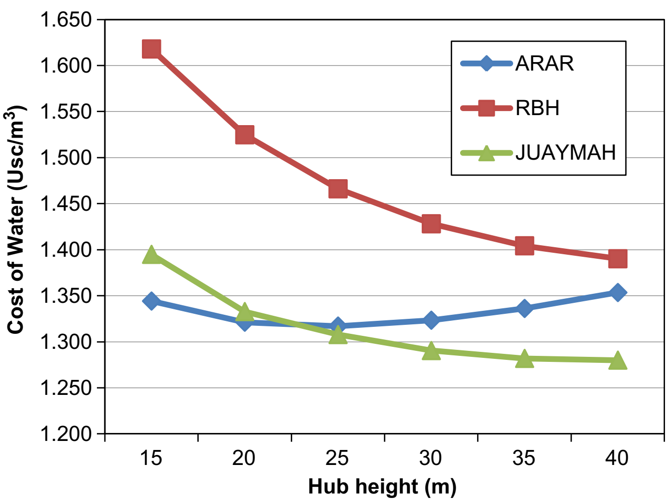


Fig. 13. Cost of wind water pumping with wind turbine hub height for a TDH of 50 m.

- Annual total water pumping capacity of 30,000 m^3 is possible from a TDH of 50 m when using 2.5 kW Proven wind turbine at all three sites.
- Cost of wind water pumping decreases as the hub height of wind turbine is increased. Cost of water pumping from a depth of TDH 50 m at Juaymah site can be as low as 1.28 US¢/m^3. However, cost saving in increasing the hub height in Arar site is not justified since variation of cost of wind water pumping is not significant as the hub height is increased.

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